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Exposure of highway maintenance workers to fine particulate matter and noise

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Abstract

In this study we assessed the mixed exposure of highway maintenance workers to airborne particles, noise and gaseous co-pollutants. The aims were to provide a better understanding of the workers exposure to facilitate the evaluation of short-term effects on cardiovascular health endpoints. To quantify the workers' exposure we monitored 18 subjects during 50 non-consecutive work shifts. Exposure assessment was based on personal and work site measurements and included fine particulate matter ($PM_{2.5}$), particle number concentration (PNC), noise (measured as the long term equivalent continuous sound level, L_{eq}) and the gaseous co-pollutants: carbon monoxide, nitrogen dioxide and ozone. Mean work shift $PM_{2.5}$ concentrations (gravimetric measurements) ranged from 20.3 µg/m^3 to 321 µg/m^3 (mean 62 µg/m^3) and PNC were between 1.6×10^4 particles/cm^3 and 4.1×10^5 particles/cm^3 (8.9×10^4 particles/cm^3). Noise levels were generally high with L_{eq} over work-shifts from 73.3 dB(A) to 96.0 dB(A); the averaged L_{eq} over all work shifts was 87.2 dB(A). The highest exposure to fine and ultrafine particles was measured during grass mowing and lumbering when motorized brush cutters and chain saws were used. Highest noise levels, caused by pneumatic hammers, were measured during paving and guardrail repair. We found moderate spearman correlations between PNC and $PM_{2.5}$ (r=0.56); PNC, $PM_{2.5}$ and CO (r=0.60 and r=0.50) as well as PNC and noise (r=0.50). Variability and correlation of parameters was influenced by work activities that included equipment causing combined air pollutant and noise emissions (e.g. brush cutters and chainsaws). We conclude that highway maintenance workers are frequently exposed to elevated airborne particle and noise levels compared to the average population. This elevated exposure is a consequence of the permanent proximity to highway traffic with additional peak exposures caused by emissions of the work-related equipment.

Introduction

Highway maintenance workers spend most of their work time in traffic and are constantly exposed to traffic-related emissions that have been linked to myocardial infarction (Bigert et al., 2003; Peters et al., 2004) as well as increased cardiovascular morbidity and mortality (Beelen et al., 2009; Hoek et al., 2002). Traffic emissions are composed of a complex mixture of particulate and volatile air pollutants on one hand and noise on the other. Levels of particulate matter (PM), carbon monoxide (CO), nitrogen oxides as well as volatile compounds including aldehydes and hydrocarbons are significantly elevated in traffic environments (Beckerman et al., 2008; Kaur et al., 2007; Riediker et al., 2003; Roorda-Knape et al., 1998; Zhu et al., 2002). An important air pollution compound in regard to health effects is the particulate fraction originating from engine exhaust, brake wear, tire wear and road surface abrasion (Riediker et al., 2004; Thorpe & Harrison, 2008). The PM fraction includes coarse particles with aerodynamic diameters between 2.5 µm and 10 µm, fine particles with diameters below 2.5 µm ($PM_{2.5}$) and ultrafine particles with diameters below 0.1µm (UFP). Direct effects of PM on the cardiovascular system are well established (Brook et al., 2010) and recent studies with focus on UFP suggest an important role of this fraction due to its small size and large surface area (Ibald-Mulli et al., 2002; Peters et al., 2006; Samet et al., 2009). While many studies have investigated health effects of traffic exposure in relation to air pollution, fewer have addressed health effects of traffic noise. There is evidence that traffic noise interacts with the cardiovascular system (Babisch, 2008) and it has been directly linked to myocardial infarction (Babisch et al., 2005; Huss et al., 2010; Selander et al., 2009) and hypertension (Fuks et al., 2011; E. van Kempen & Babisch, 2012). Although elevated noise levels during resting periods and at night may be most critical, cumulative exposure to high noise levels in occupational settings have also been related to hypertension (Sbihi et al., 2008; Stokholm et al., 2013; E. E. van Kempen et al., 2002).

Workers in traffic environments are exposed continuously to particles and noise and may therefore be at higher risk for cardiovascular diseases compared to the average population. Elevated exposure to air pollutants have been reported for policemen (Crebelli et al., 2001; Riediker, et al., 2003) and workers exposed to motor exhaust (Lewne et al., 2007). Noise was not measured in these studies. Only a few studies describe combined particle and noise measurements at traffic locations (Boogaard et al., 2009; Can et al., 2011; Ross et al., 2011) and the same is true for combined health effects that were assessed in cohort studies only recently (Beelen, et al., 2009; Fuks, et al., 2011; Huss, et al., 2010; Selander, et al., 2009) and only for long term effects. Highway maintenance workers are frequently exposed to air pollutants and noise originating from road traffic or working equipment as generators or brush cutters. This mixed exposure may contribute to an increased risk for cardiovascular diseases. Our exposure assessment for this worker population serves as the basis to evaluate probable cardiovascular health effects and to develop strategies to better protect the workers' health.

The aims of our study were to better define the workers' exposure to traffic stressors, particularly inhalable particles and noise, for the purpose of evaluating short-term effects on cardiovascular health endpoints. Exposure data were collected in collaboration with 8 maintenance centers of the Swiss Road Maintenance Services located in the cantons Bern, Fribourg and Vaud in western Switzerland. Repeated measurements with 18 subjects were conducted during 50 non-consecutive work shifts between Mai 2010 and February 2012, equally distributed over all seasons. We hypothesized that the workers' exposure significantly exceeds the exposure of the average population what could lead to an increased risk for cardiovascular diseases. In this paper we present the mixed exposure of highway maintenance workers to $PM_{2.5}$, PNC and noise as well as to the co-pollutants carbon monoxide, nitrogen dioxide (NO_2) and ozone (O_3).

Methods

Study design

To assess the workers exposure to inhaled particles and noise as well as gaseous co-pollutants, we used a methodology based on personal and work site measurements. To examine $PM_{2.5}$ and noise exposure the subjects were equipped with a personal dust monitor and a noise dosimeter. Additional parameters were assessed at the work site with measurement devices fixed on a hand-cart that was collocated with the workers in the field. Sample inlets were attached to a plate on the cart handle about 1 m above ground. Work site measurements included particle number concentration (PNC), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3) as well as sampling of $PM_{2.5}$ for gravimetric analysis and PM_4 for determination of elemental (EC) and organic carbon (OC) levels. In parallel we also measured temperature and humidity. Real-time measurements ($PM_{2.5Realtime}$, noise, PNC, CO, temperature and humidity) were handled in a time resolution of 1 minute and merged according to time. Work site filter samples (PM) as well diffusive samplers (NO_2, O_3) were exposed over full work shifts. Measurements were conducted during 50 work shifts between May 2010 and February 2012 in collaboration with the Swiss Road Maintenance Services on highways in western Switzerland. The Ethical Committee from the University of Lausanne approved the study, and all research volunteers provided written consent.

Measurement of fine particulate matter

$PM_{2.5}$ was measured by light scattering in real-time (1 minute resolution) using a personal DataRam particulate monitor pDR1000 (Thermo Scientific, Waltham, MA, USA) that was attached on the subjects' back. As the DataRam is known to overestimate $PM_{2.5}$ in humid conditions, the data was corrected for relative humidity (RH) according to Richards et al. 1999 (Richards et al., 1999): $PM_{corrected}$=exp(0.68*ln(1-RH)+0.35)*$PM_{measured}$). $PM_{2.5}$ was also measured gravimetrically with sampling on 37mm PTFE filters #225-1709 from SKC (SKC Inc. Eighty Four, PA, USA) at the work site. The filters were placed in a Personal Environmental Monitor PEM #761-203B (SKC) connected to a Leland Legacy sampling pump (SKC) with a flow rate of 10 liters per min. After storage in standard atmosphere for at least 24 hours the filters were weighted before and after exposure with a Sartorius Microbalance from Mettler Toledo (Greifensee, Switzerland). Exposed filters were always compared to a laboratory blank to adjust for temperature related variations. For quality assurance (QA), gravimetric measurements were performed in duplicates on 16 % of the assessments: results differed in average by 15.7 %.

Determination of elemental, organic and total carbon

Elemental and organic carbon content of PM_4 was determined using plasma-cleaned 37 mm Pallflex quartz-filters 2500QAT-UP (Pall Corporation, Port Washington, NY, USA). Sampling was performed at the work site with a flow sampler S2500 from DuPont (Wilmington, DE, USA) and a Casella Dust Cyclone (Ideal Industries, Sycamore, IL) at a sampling rate of 2 liters per minute. Elemental carbon (EC) and Organic carbon (OC) were determined following the standard NIOSH 5040 procedure (Birch & Cary, 1996). Carbon measurements were always corrected with field blanks. EC samples from 16 work shifts were below the quantification limit of 3 $\mu g/m^3$ for a sampling duration of 8 hours. In order to calculate an adequate mean and SD over all work shifts we used a tobit regression to account for this not quantified data. For QA, 12 % of the carbon measurements were performed in duplicates: results differed in average by 6.1 % for OC and 36.6 % for EC.

Measurement of ultrafine particles

Particle number concentrations were measured at the work site with a miniDiSC, developed at the University of Applied Sciences Northwestern Switzerland (Fierz et al., 2011). For sampling we used the 0.8 μm-cutoff impactor and Nalgene 180 clear plastic tubing. Logging interval was 1 second, for analysis data were averaged over 1 minute. QA measurements confirmed validity of these measurements under highway conditions for the particle size range from 16 nm to 300 nm (Meier et al., 2013).

Measurement of gaseous pollutants

Carbon monoxide was measured at the work site with the CO monitor T15n (Langan Products, San Francisco, CA, USA) in 1 minute resolution. NO_2 and O_3 concentrations were measured with short-term diffusive samplers from Passam AG (Männedorf, Switzerland) exposed at the work site over full work shifts. Samples were always taken in duplicates and analyzed in the laboratories of Passam AG. O_3 duplicates differed on average by 24.9 %; NO_2 samples by 6.7 %. The quantification limit for O_3 samples was 7.6 ppb for an exposure of 8 hours which was not achieved on 24 work shifts (mostly during winter time). In order to calculate an adequate mean and SD over all work shifts we used a tobit regression to account for this not quantified data.

Noise measurement

Noise was measured with the noise dosimeter type 4500 from Bruel&Kjaer (Nærum, Denmark) in standardized ISO85-mode with a measurement range from 70-140 dB(A), A-Filter for RMS detector and C-Filter for peak detector. Time weighting was fast, values were stored in 1 minute resolution. Microphones were attached near the ear of the subjects by clipping them to the shirt or jacket. During lunch and quiet work tasks the lower threshold of 70 dB(A) was not always achieved (34 % of all intervals over 1 minute). For the calculation of an adequate long term equivalent continuous sound level (L_{eq}) over the full work shift these non-detected noise levels were replaced with 67 dB(A). As sensitivity analysis these values were replaced with 20 dBA which resulted on average in a 0.05 dB lower L_{eq} over the full work shift (SD 0.1). The small impact of this non quantified values is due to the logarithmic nature of noise and the relatively high noise levels beside the quiet periods. In order to adapt noise levels to the use of hearing protectors we took notes of the exact time periods when the subjects used ear plugs or ear muffs. L_{eq}-corrections were based on the A-weighted L_{eq} as we did not measure the C-weighted L_{eq} or frequency bands. Noise levels were corrected by 25 dB if ear muffs (SNR 30) and by 20 dB if preformed earplugs (SNR 25) were used. Correction factors were defined according to proposed real-world corrections for hearing protectors (Dantscher et al., 2009).

Measurement of temperature and humidity

Temperature and humidity were measured with HOBO data loggers U12-012 (Onset Computer Corporation, Cape Cod, MA, USA) that were fixed to the personal dust monitors as well as to the hand cart at the work site. Data was logged in 1 minute resolution.

Stationary measurements of air pollutants

Time matched measurements of PM_{10}, PNC, CO, NO_2 and O_3 of the stationary measurement stations in Härkingen (highway site) and Payerne (countryside), Switzerland, were obtained from the Swiss National Air Pollution Monitoring Network (NABEL) in a time resolution of 10 minutes. Data were provided by the NABEL and MeteoSwiss (EMPA, 2011).

Record of activity, work site and the use of hearing protectors

The activity and type of the work site of the subjects was recorded by the researcher accompanying the subjects during their work shift. Activities and work sites were translated into predefined codes attributed to the corresponding time periods. Work sites were defined as: indoor, in the garage of the maintenance center, in the car/truck, at roadside, off-road (>100 m away from highway or behind a major obstacle) or inside tunnels. Periods when the subjects were using earplugs or earmuffs were recorded similarly. Periods were flagged if a subject was away from the measurement devices at the work site. Away was defined as not being in the same working environment for more than 3 minutes i.e. working at a different place; e.g. being outside while cart is inside car or working at a distance of more than 50 meters from the hand cart.

Data treatment and statistical analysis

Data of all real-time measurements were processed with the standard software delivered with the corresponding device and imported into STATA (StataCorp. 2011. Stata Statistical Software: Release 12. College Station, TX: StataCorp LP). Activity, work site, use of hearing protectors and other field remarks were attributed to the data according to time. STATA was used for statistical analysis. Linear regression models of log-normal distributed air pollution data were calculated with logarithmized data (using natural logarithm). Tobit models (Tobin, 1958; Wild et al., 1996) were used to calculate means, standard deviations and regression models for parameters with values below the quantification limit (O_3 and EC): Tobit models were applied on logarithmized data followed by the calculation of arithmetic mean and standard deviation with standard formula based on geometric statistics assuming log normal distributions.

Imputation of missing data

Missing and excluded real-time data were replaced with estimations in order to calculate adequate means over full work shifts. Missing air pollution data were replaced by estimates based on a correlated pollutant extrapolated to the distribution of the missing pollutant for the same subject, activity and type of work site. Estimations of noise data were based on the parallel noise measurement of the second subject if both subjects worked at the same site. If no parallel noise data were available, values were replaced based on existing data for the same subject, activity and type of work site. Missing values were not replaced if the activity and work site of the subject was not known. Estimations were only considered for the calculation of the averaged exposure over work shifts and not for calculation of activity specific exposure where missing were ignored. If a real-time variable was missing for more than 50% of a work shift the work shift was not considered for summary statistics of this variable.

Results

Characterization of the data base

During 38 work shifts, two subjects were equipped with personal measurement equipment, while only one subject was equipped during 12 work shifts. This resulted in a total of 88 personal assessments during 50 work shifts. The duration of a work shift was 8.5 hours (SD 25 min), including work breaks. This was slightly shorter than a normal work shift as the subjects underwent a health assessment before maintenance work and exposure measurement started. During maintenance work the subjects conducted the usual work tasks and did not make adaptations for the study.

The analysis of $PM_{2.5Realtime}$ is based on data from 86 personal assessments during 49 work shifts. $PM_{2.5Realtime}$ of two subjects during one work shift was not recorded. A total of 0.5 % of the $PM_{2.5Realtime}$ data during the 86 assessments were missing because the DataRam was not operational; 0.4 % were excluded because the relative humidity was higher than 95 % or the instruments were influenced by splash water (for example during car cleaning with high pressure water). A total of 90 % of missing and excluded $PM_{2.5Realtime}$ values were replaced with estimations based on subject, activity, work site and daily variation of a correlating variable. The analysis of personal noise measurements is based on data from 82 personal assessments during 50 work shifts with 3.6 % missing data that were replaced with estimations. Six assessments were not used as more than 50 % were missing because of microphone and battery failures. Exposure to UFP is based on data from 50 work shifts with 4.8 % missing; exposure to CO on data from 49 work shifts (no data for one work shift because of battery failure). UFP and CO data were excluded for the individual assessments if subjects were absent, which was the case during 4.6 % of the exposure measurements. Seventy-five percent of the missing or excluded UFP data and 71 % of the excluded CO data were replaced with estimations. Data could not be replaced if the activity and work site of a subject was not known. Data from PTFE filter samples were available for all 50 work shifts; data from Quartz filter samples to determine EC and OC fractions for 49 work shifts (pump failure during one shift). Data of NO_2 and O_3 samples were available from all 50 work shifts. Temperature and humidity measurements were also available for all 88 personal assessments during all 50 work shifts.

Work activities

The subjects spent most of the time driving between maintenance centers and work sites or between work sites (19.2 %), followed by preparatory work (12.5 %), usually in the garage at the maintenance center. Work tasks at the maintenance center also included office work (5.2 %) and maintenance work at the center (1.8 %). Maintenance work in the field included mowing with brush cutters (8.7 %), collect fallen leaves, stones and litter (cleaning 7.0 %), maintenance of electric installations outside (3.1 %) and inside tunnels (1.4 %), signalization (4.8 %), repair guard rails (3.1 %), lumbering (2.0 %) and other activities (5.8 %) including small paving repair work, cleaning sewer conduits, snow plowing, reparation of deer fences, up/unload truck and application of herbicides for weed control. Lunch and other work breaks, which were included in the exposure measurements, contributed to 20.7 %. Subjects were occasionally absent and activity therefore not attributed to the measured data for 4.6 %.

Activity specific exposure to particles and noise

Real-time exposure data of particles and noise were analyzed separately for the different maintenance activities. For the activity specific analysis we calculated the averaged noise level as well as geometric means (GM) and geometric standard deviations (GSD) of particle exposure shown in Table 1. Figure 1 shows scatter plots with the activity specific median and quartile-range as well as the arithmetic means of $PM_{2.5Realtime}$, PNC and L_{eq} for each activity. We have seen that mowing, lumbering and pavement repair combined elevated fine and ultrafine particle concentrations with high noise levels. Electrical maintenance work in tunnels was related to the highest PNC and noise levels but concentrations of $PM_{2.5}$ inside tunnels were surprisingly low. Mean geometric diameters of UFP were between 28 nm and 55 nm. Diameters were smaller for activities in proximity to traffic; the smallest diameters were encountered during mowing, lumbering and pavement repair (below 32 nm). During mowing and cleaning we found very heterogeneous particle levels. Noise levels were constantly high during most of the maintenance activities. Levels over 90 dB(A) were measured inside tunnels or during the use of noisy working equipment.

Exposure during work shifts

Arithmetic means of exposure during work shifts were calculated to assess the daily exposure of the subjects. Summary statistics are given in Table 2; box plots for averaged data of work shifts are provided in Figure 2. High particle concentrations were measured during work shifts with lengthy mowing events. Work shifts including mowing or cutting wood were usually also related to high OC and EC concentrations. Noise levels averaged over full shifts were usually high, exceeding 85 dB(A) on 46 % of the valid assessments. Correction of ear noise levels by 25 dB for ear muffs and 20 dB for ear plugs led to significantly decreased ear noise exposure. However, it was still above 85 dB(A) during 13 assessments (16%). The variability of exposure parameters between work shifts was relatively high with standard deviations from

50 % (NO_2) to more than 100 % for $PM_{2.5Realtime}$, PNC, noise and CO. The variability within shifts was even higher with differences of more than 200 %, except for temperature and humidity that showed lower variability within than between shifts (Table 2).

Exposure data collected during work shifts were compared to data of two stationary measurement stations, situated next to the Highway A1 in Härkingen, Switzerland, and a station located in the countryside in Payerne, Switzerland, operated by the Swiss National Air Pollution Monitoring Network and MeteoSwiss. Air pollution parameters of both stations were significantly lower than measurements from the exposure assessments, only the ozone levels were higher (Table 3). Stationary data for corresponding time periods of the different maintenance activities are provided in Table 1.

Correlations of air pollutants, noise and meteorological parameters

Personal $PM_{2.5Realtime}$ concentrations corresponded well to $PM_{2.5Mass}$ measured at work site (Pearson correlation = 0.88). This correlation was slightly improved by correcting $PM_{2.5Real\text{-}time}$ for humidity (without correction Pearson correlation = 0.83). Personal $PM_{2.5Realtime}$ measurements running in parallel for two subjects correlated well (Pearson correlation = 0.88 during 37 parallel assessments). Personal measurements of noise exposure during full work shifts were moderately correlated (Pearson correlation = 0.54 during 34 parallel assessments). Spearman correlations between the different airborne pollutants and noise were calculated based on the work shift averages and are shown in Table 4. Moderate correlations were found between PNC, CO and $PM_{2.5}$. Noise was moderately correlated to PNC but only weakly to $PM_{2.5}$. Coefficients of linear regression models between logarithmized work shift averages are provided in the supplemental Table S1 in the online edition. Table 3 shows the correlations of the work shift averages to time matched data from the fixed stations in Härkingen and Payerne:$PM_{2.5}$ and O_3 were moderately correlated with both stations, NO_2 showed weak correlation to the station at the highway. PNC and CO did not correlate with stationary data.

Discussion

Exposure assessments during highway maintenance work showed that maintenance workers were regularly exposed to elevated particle and noise levels as compared to the average population. Particle as well as noise exposure varied in relation to different maintenance activities from clean and quiet conditions during office work to conditions with elevated particle and noise exposure during activities at road-side as signalization or electric maintenance work. Exposure to particles and noise reached very high levels if a work task included the use of particle and/or noise emitting working equipment such as brush cutters, chain saws, generators and pneumatic hammers. The low UFP diameters that were measured during the use of motorized working equipment indicate that combustion emissions from theses small engines contributed substantially to the high particle levels. However, dispersion of soil dust, release of plant sap and pollen as well as resuspension of deposited PM may also have played a role – although more likely for fine and coarse particle mass rather than total particle number. The high UFP and noise levels in tunnels can be explained by constant particle and noise emissions of highway traffic. Low $PM_{2.5}$ levels inside tunnels are likely a consequence of clean environmental conditions and a good ventilation of the tunnel: UFP do not stay inside the tunnel very long and photochemical processes leading to accelerated agglomeration do not take place due to lacking UV-radiation. Elevated and inhomogeneous particle levels during cleaning were mainly influenced by two work shifts during which the subjects were followed by a mowing tractor causing high particle emissions. The high $PM_{2.5}$ levels during weed control can neither be explained with working equipment nor with traffic volume or environmental background levels. Although gravimetric $PM_{2.5}$ measurements of the two affected work shifts corresponded well to the real-time data, we cannot exclude that the light scatter measurements were influenced by herbicide spray aerosols. High $PM_{2.5}$ concentrations during deer fence repair were related to elevated environmental background concentrations, low particle concentrations during truck loading can be explained by the work sites situated either off road or underneath a highway bridge in the countryside. Low $PM_{2.5}$ concentrations during snow-plow cannot be explained conclusively, but were likely a consequence of local precipitations washing out particles. High noise levels during guardrail repair were caused by assembling the metal barriers and reached very high levels when a pneumatic hammer was used to drive guardrails into the ground.

To calculate the contribution of different maintenance activities to the total particle exposure we multiplied the duration of an activity during the 50 work shifts of exposure assessment with the mean exposure level (Figure 3). We could see that mowing was the biggest contributor by far as it combined high exposure with long duration. However, these contributions cannot be generalized for individual workers as they conducted certain activities more of less often than the mixed sample of workers.

All exposure parameters showed a high variability within and between work shifts. This variability can be explained by the mix of different maintenance activities and changing environmental background on different work shifts. Exposure during “clean” activities were comparable to levels at the highway site in Härkingen and corresponded to data found in the literature: $PM_{2.5Realtime}$ concentration during driving (arithmetic mean 29.0 $\mu g/m^3$) is in the same range as levels inside patrol cars in North Carolina (Riediker, et al., 2003) and Swedish taxi drivers but lower than exposures involving Swedish bus and lorry drivers (Lewne et al., 2006). The geometric mean of $PM_{2.5Realtime}$ during preparatory work was lower than values for Swedish garage workers working with petrol and diesel vehicles (Lewne, et al., 2007). PNC during roadside activities without particle emitting working equipment were comparable to measurements at a highway toll station in Taiwan (Cheng et al., 2010) if adapted for the measured size range of the miniDiSC (Meier, et al., 2013). On the other hand they were clearly lower than reported for the 9-lane Freeway 405 in Los Angeles (Zhu, et al., 2002). However, comparison of PNC with literature data has to be interpreted with care as PNC have a high temporal and spatial variability. Concentrations of EC and OC were lower than values measured at a highway toll station in Taiwan (Shih et al., 2008) but comparable to previously published concentrations at traffic locations that are summarized by Shih et al. 2008 (Shih, et al., 2008). NO_2 levels were more than twofold higher than at the highway site in Härkingen and 1.4 to 3.8 fold higher than reported for other traffic locations (Can, et al., 2011; Gilbert et al., 2003; Ross, et al., 2011) and inside patrol cars (Riediker, et al., 2003).

Maintenance activities with motorized equipment were associated with strongly elevated levels of both particles and noise. This seems to be the main reason why the correlation between $PM_{2.5}$ and PNC was higher than previously reported for traffic environments (Boogaard, et al., 2009; Boogaard et al., 2010) and also explain the correlation between $PM_{2.5}$ and CO. Moderate correlations of PNC and CO to noise can be attributed to simultaneous combustion and noise emissions from motorized work equipment and highway traffic. The low correlation of $PM_{2.5}$ and noise can be explained by the dependency of $PM_{2.5}$ on the environmental background rather than local combustion emissions. In contrast to previously published data for traffic locations (Davies et al., 2009; Ross, et al., 2011) we did not see any correlation between noise and NO_2. Interestingly NO_2 and EC were very well correlated and the only two pollutants that only showed weak correlations with any other parameter. High correlation between these two pollutants in proximity to highways have been described before (Ross, et al., 2011). Personal $PM_{2.5\text{Real-time}}$ and work site $PM_{2.5\text{Mass}}$ correlated well but the range of the real-time measurements was wider. These differences are likely a consequence of the different measurement techniques and real-time values exceeding the gravimetric values by 50 % or more can be explained by overestimation of the personal DataRam (Liu et al., 2002). Despite generally small distances between the two measurements (< 10 m), we suggest that large measurement differences (more than 70 % during 9 work shifts) were due to different distances from pollution sources.

We could confirm our hypothesis that maintenance workers are exposed to elevated particle and noise levels compared to the average population. Mean $PM_{2.5}$ levels were about 3 to 8 times higher than residential exposure of the Swiss population represented by the SAPALDIA cohort (6.9 µg/m^3 – 24.9 µg/m^3) (Liu et al., 2007). Noise levels were considerably higher than residential traffic noise during daytime for the same cohort (50.5 dB(A)) (Dratva et al., 2012). PNC were about 3 to 20 times higher when compared to residential exposure in four European Cities (4.5×10^3 particles/cm^3 - 2.6×10^4 particles/cm^3 in the size range 7 nm - 3 µm) (Puustinen et al., 2007). Although exposure to air pollutants was elevated in comparison to environmental background concentrations, no parameter reached critical values in comparison to 8 hour occupational exposure limits as defined by Swiss legislation (SUVA, 2012). No statement can be made about O_3 exposure which is regulated with a short-term limit that cannot be compared to the work shift mean that we measured. This short-term limit may have been exceeded, as this was the case at the highway site in Härkingen. PNC cannot be compared to limits as there are no regulations for this parameter. However, PNC showed a very large increase in comparison to environmental background concentrations. Noise levels levels frequently exceeded 85dB(A), a typical limit for prevention of hearing loss. Hearing protectors were available at all time and usually used by workers as needed, although less often when noise was caused by highway traffic but not the work task itself.

The elevated exposure to particles may lead to an elevated cardiovascular risk even if occupational exposure limits are not exceeded. Assuming an average non-work related background exposure of 20 $\mu g/m^3$ the additional exposure of an 8.5 hour work shift with a mean exposure of 62 $\mu g/m^3$ leads to an increase of almost 15 $\mu g/m^3$. According to current knowledge, such short-term elevations lead to an increased relative risk for daily cardiovascular mortality of 0.6 % to 1.5 % (Brook, et al., 2010). Extrapolated on a full year with 235 workdays the occupational contribution is responsible for an increase of 10 $\mu g/m^3$. On the long-term this additional exposure leads to an elevated risk for cardiovascular mortality of a factor of 1.06 to 1.76 (Brook, et al., 2010).

Conclusion

Highway maintenance workers are exposed to elevated levels of fine and ultrafine particles as well as noise compared to the average population. This elevated exposure is a consequence of close proximity to highway traffic but peak exposure levels occur when motorized working equipment as brush cutters, chain saws, generators and pneumatic hammers are used. The largest potential for occupational exposure reduction seems to be with these devices. Although exposure to air pollutants were not critical if compared to occupational exposure limits, the elevated exposure to particles and noise may lead to a higher risk for cardiovascular diseases in this worker population.

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Table 1: Personal, work site and time matched stationary measurements of particles and noise according to maintenance activity. Geometric means (GM) and geometric standard deviations (GSD) are given for particle exposure, averaged L_{eq} for noise.

			Personal assessments				Work site assessments		Fixed station NABEL	
Work task	During # work shifts[a]	# of subjects	GM of $PM_{2.5Realtime}$ [µg/m^3] (GSD)	# obs[b] $PM_{2.5Realtime}$	L_{eq} [dB(A)] (SD [dB(A)])	# obs[b] L_{eq}	GM of PNC [particles/cm^3] (GSD)	# obs[b] PNC	GM of PM_{10} Härkingen (GSD)	GM of PNC Härkingen (GSD)
Driving	49[c]	18	18.4 (3.0)	8,038	80.1 (5.9)	7,808	23,192 (2.9)	4,842	17.8 (1.9)	19,329 (2.9)
Preparation	48	18	34.0 (3.1)	5,169	83.7 (8.3)	5,005	19,929 (2.8)	3,074	19.0 (1.9)	23,470 (2.9)
Mowing	13	9	129.6 (4.7)	3,881	90.8 (7.1)	3,503	108,773 (7.1)	2,245	22.9 (1.6)	17,152 (2.8)
Cleaning	9	9	30.5 (3.6)	3,201	85.2 (6.2)	2,765	28,919 (5.8)	1,824	20.8 (2.0)	30,412 (2.6)
Signalization	18[c]	16	21.8 (3.0)	2,070	87.2 (6.6)	1,867	28,032 (2.9)	1,274	18.7 (1.7)	18,851 (2.7)
Repair guardrails	5	8	27.1 (2.2)	1,405	96.7 (7.4)	1,370	21,170 (2.6)	794	15.6 (1.3)	21,881 (2.3)
Office work	6[d]	3	15.3 (2.8)	1,351	72.0 (8.0)	1,349	11,981 (1.5)	1,071	22.3 (1.8)	31,113 (2.7)
Electrical maintenance without tunnel	5[c]	4	12.9 (2.9)	1,163	84.3 (7.2)	1,357	13,840 (3.2)	808	13.0 (1.5)	17,460 (2.6)
Electrical maintenance in tunnel	3	4	12.8 (2.4)	806	92.3 (5.3)	692	64,741 (2.9)	477	13.2 (1.5)	34,649 (1.7)
Maintenance-work at maintenance center	2	3	24.0 (2.2)	833	80.7 (6.7)	833	14,148 (2.2)	444	17.5 (1.3)	17,497 (2.5)
Lumbering	4	3	60.3 (2.3)	745	95.8 (7.0)	715	84,238 (3.6)	496	28.4 (2.2)	16,827 (3.0)
Sewer cleaning	2	4	25.8 (2.7)	607	85.1 (5.9)	539	18,760 (2.6)	327	23.1 (1.3)	21,427 (1.5)
Load truck	7[e]	9	20.8 (2.5)	450	83.5 (8.0)	438	8,272 (2.4)	231	11.4 (1.9)	8,262 (2.8)
Paving repair	3	2	45.0 (2.5)	319	98.9 (8.1)	319	82,555 (2.5)	318	26.6 (1.2)	22,358 (2.5)
Weed control	2[d]	2	53.2 (2.9)	277	80.3 (5.6)	277	12,008 (2.0)	85	13.0 (1.0)	29,933 (2.1)
Snow-plow[f]	1	1	7.0 (2.6)	273	82.0 (4.5)	274	27,639 (2.6)	270	71.2 (1.1)	95,947 (1.5)
Repair deer fence	2	1	38.9 (1.6)	265	82.0 (5.8)	168	8,069 (2.4)	257	49.2 (1.1)	8,099 (1.4)
Break	50[c/d]	18	20.1 (3.3)	9,034	76.5 (8.5)	8,387	10,950 (2.5)	4,924	19.9 (1.9)	19,485 (2.9)

[a] shift only counted if activity was performed for more than 15 minutes
[b] number of measured minute averages
[c] one work shift less for $PM_{2.5Realtime}$
[d] one work shift less for PNC
[e] on work shift less for noise
[f] precipitations at work site but not at site of fixed station

Table 2: Summary of exposure parameters per work shift with arithmetic mean and range as well as standard deviation (SD) between and within work shifts

	Unit	Mean	Min	Max	Between shift SD[a]	Within shift SD[b]	# of work shifts	# of personal or work site assessments
$PM_{2.5Realtime}$	µg/m³	79.5	9.0	723.5	113.4 (143%)	167.1 (210%)	49	86 [g]
$PM_{2.5\ Mass}$	µg/m³	61.8	20.3	321	53.5 (87%)	- [f]	50	50 [h]
PNC	#/cm³	88,660	15,524	406,534	97,670 (110%)	198,024 (223%)	50	50 [h]
UFP size[c]	nm	48.0	30.4	78.7	9.6 (20%)	15.9 (33%)	50	50 [h]
L_{eq}	dB(A)	87.2	73.3	96.0	5.0 (317%)	8.9 (770%)	50	82 [g]
Peak noise[d]	events	3.6	0.0	27.0	4.9 (135%)	- [f]	50	82 [g]
CO	ppm	0.8	0.1	5.5	1.0 (117%)	1.9 (228%)	49	49 [h]
NO_2	ppb	57.6	15.6	155.2	28.7 (50%)	- [f]	50	50 [h]
O_3	ppb	11.4	b.q.[e]	46.5	9.7 (85%)	- [f]	50	50 [h]
OC	µg/m³	24.8	3.4	129.5	17.8 (72%)	- [f]	49	49 [h]
EC	µg/m³	4.7	b.q.[e]	18.6	3.4 (73%)	- [f]	49	49 [h]
Temperature	°C	20.2	8.1	32.6	5.9 (29%)	3.6 (18%)	50	88 [g]
Humidity	%	51.1	34.9	76.4	10.0 (19%)	9.0 (18%)	50	88 [g]
Duration	hh:mm	08:31	07:32	09:53	00:25 (5%)	- [f]	50	88 [h]

[a] considering averages over work shift
[b] considering minute averages during work shifts
[c] geometric mean diameter
[d] peak noise events with noise levels above 135dB(C)
[e] below quantification limit (7.6 ppb for O_3; 3 µg/m³ for EC)
[f] only assessed for full work shift
[g] personal assessment
[h] work site assessment

Table 3: Time matched air pollutant data of two stationary sites located near to a highway and in the countryside. Spearman correlations are based on averages over work shifts. Data provided from the Swiss National Air Pollution Monitoring Network and MeteoSwiss.

Härkingen (Highway site)

	PM_{10}	PNC	CO	NO_2	O_3	Temperature	Humidity
unit	µg/m^3	#/cm^3	ppm	ppb	ppb	°C	%
mean	24.8	35,511	0.3	25.1	22.3	13.0	66.6
SD	17.7	25,092	0.1	12.3	16.5	9.0	12.8
min	6.6	3,395	0.1	4.3	1.2	-7.1	38.0
max	115.0	115,822	0.7	51.2	73.8	30.5	85.7
Spearman correlation to exposure assessments	0.48*[a] 0.39*[b]	0.02	0.00	0.32	0.70*[d]	0.89*	0.64*
Payerne (Countryside)							
mean	19.2	-[c]	0.2	7.6	33.6	12.6	69.1
SD	13.3	-[c]	0.1	4.1	17.3	9.0	14.6
min	2.8	-[c]	0.1	2.8	4.3	-7.4	35.8
max	79.8	-[c]	0.6	18.8	71.9	29.5	93.7
Spearman correlation to exposure assessments	0.49*[a] 0.44*[b]	-[c]	0.14	0.03	0.74*[d]	0.90*	0.62*

[a] correlation to $PM_{2.5Real\text{-}time}$
[b] correlation to $PM_{2.5Mass}$
[c] no data available
[d] correlation on measured data only (not considering estimates for not quantified samples)
*correlation significant (p<0.01)

Table 4: Spearman correlations between air pollutants, noise and meteorological parameters averaged over work shifts (arithmetic means)

	$PM_{2.5Realtime}$	$PM_{2.5Mass}$	PNC	L_{eq}	CO	NO_2	O_3	EC	OC	Temperature
$PM_{2.5Mass}$	0.80*	1.00								
PNC	0.56*	0.48*	1.00							
L_{eq}	0.28	0.25	0.50*	1.00						
CO	0.50*	0.51*	0.60*	0.40*	1.00					
NO_2	-0.33	-0.20	-0.02	-0.02	-0.09	1.00				
O_3	0.27	0.30	-0.13	0.07	0.21	-0.19	1.00			
EC	-0.10	-0.02	0.02	-0.10	-0.09	0.70*	-0.16	1.00		
OC	0.67*	0.64*	0.57*	0.19	0.54*	-0.14	0.11	-0.03	1.00	
Temperature	0.14	0.29	-0.06	0.03	0.25	-0.09	0.68*	0.01	0.07	1.00
Humidity	-0.08	-0.10	0.15	-0.03	-0.21	0.01	-0.47*	0.11	-0.11	-0.32

* correlation significant ($p<0.01$)

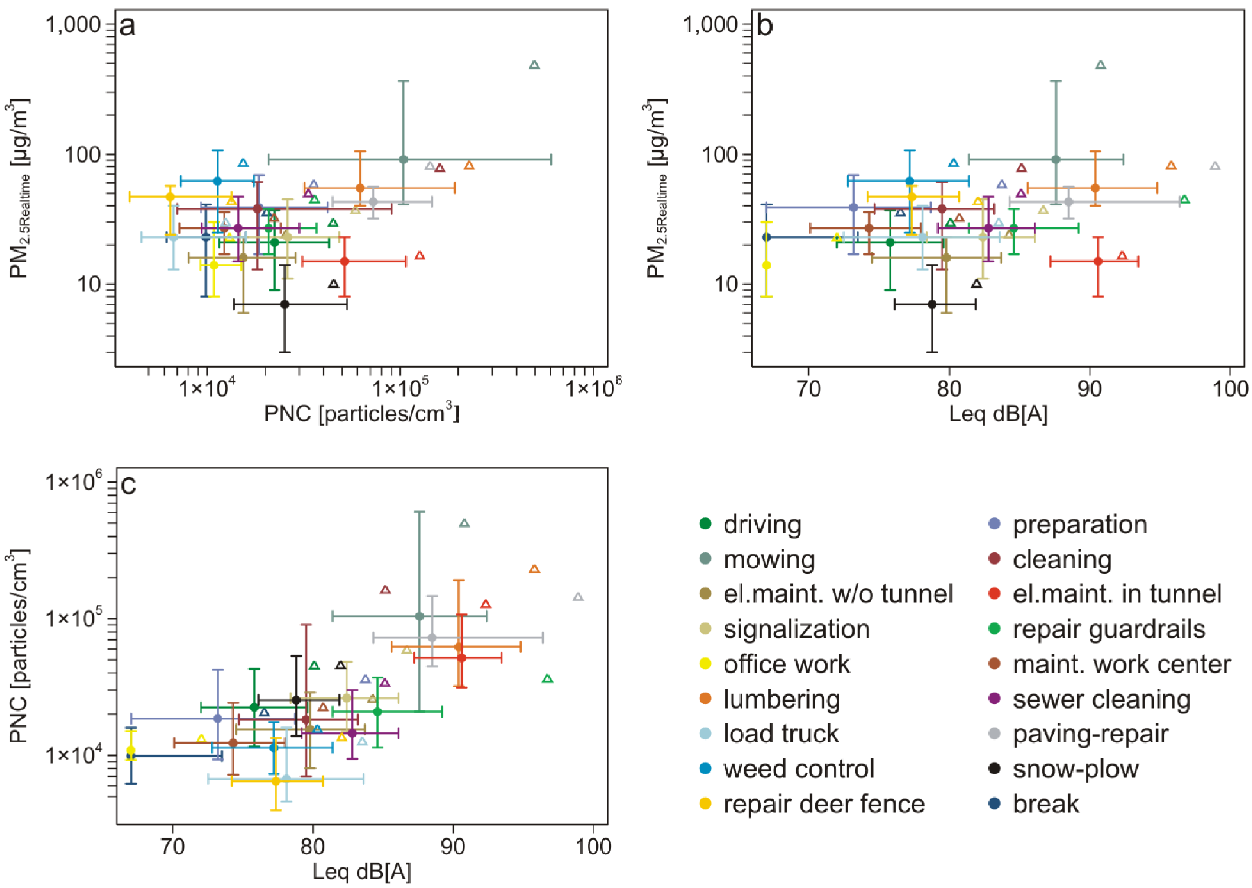

Figure 1: Scatter plots with activity specific exposure to $PM_{2.5Realtime}$, PNC and noise. Graphs show medians with quartiles (cross) and arithmetic means (triangles) of exposure parameters for the different activities.

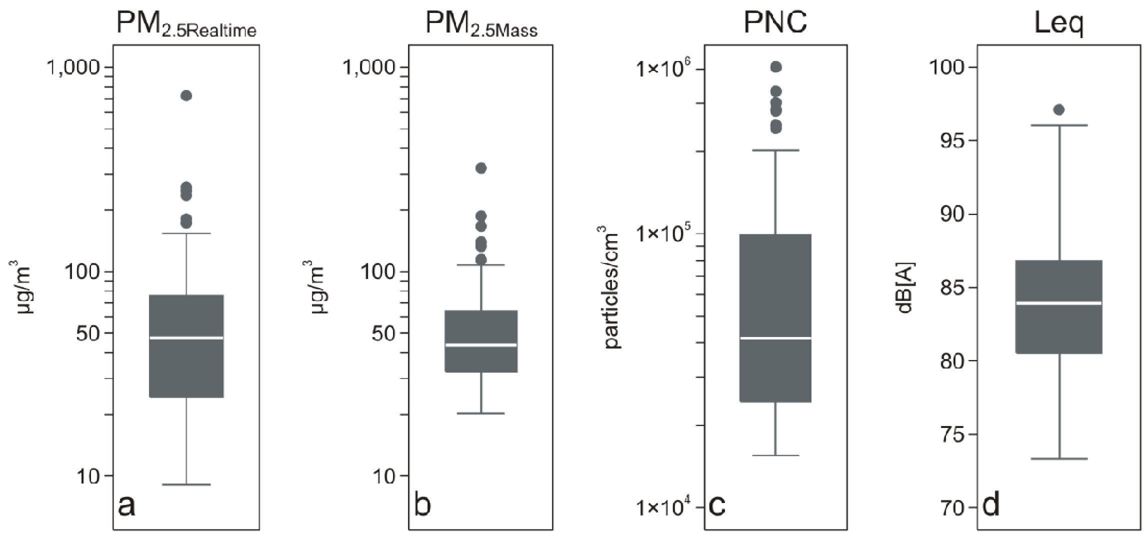

Figure 2: $PM_{2.5}$, PNC and L_{eq} averaged over work shifts; a) Personal $PM_{2.5Real\text{-}time}$; b) Gravimetrically measured $PM_{2.5Mass}$ at work site; c) Particle number concentrations at work site; d) Personal noise exposure

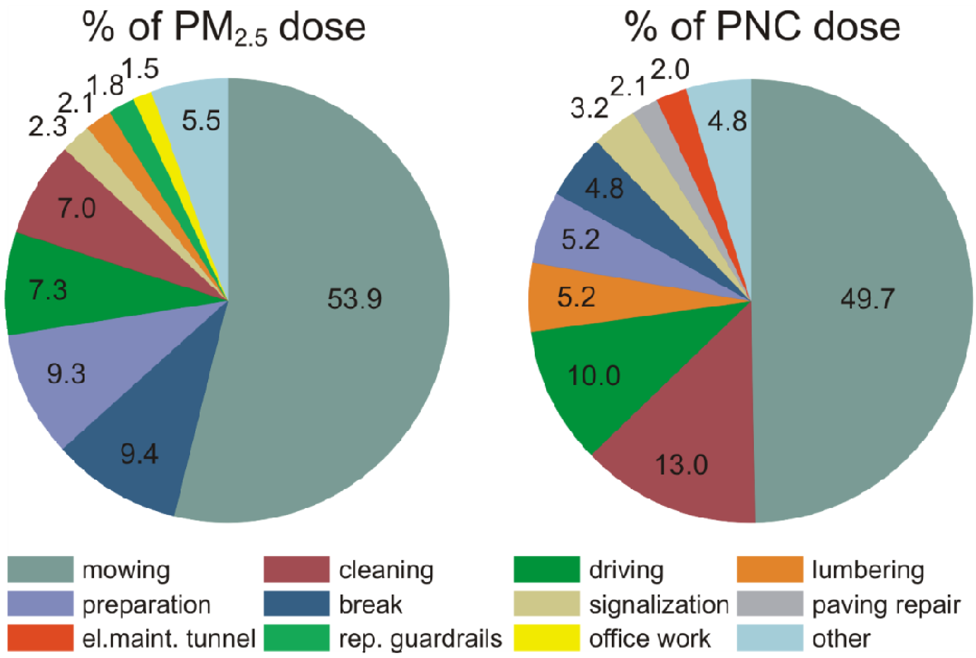

Figure 3: Activity dependent contribution to the total $PM_{2.5}$ and PNC dose during the exposure assessment

1.1.3 Supplemental Information

Imputation of missing data

Missing air pollution data were replaced by estimates based on a correlated pollutant extrapolated to the distribution of the missing pollutant for the same subject, activity and type of work site. The following formula was applied:

$$\mathbf{Mx} = e^{log\,\mathbf{Msaw\_mean} + (log\,\mathbf{Mx\_corr} - log\,\mathbf{Mcorr\_mean})} * \frac{\mathrm{SDlog}\mathbf{Msaw}}{\mathrm{SDlog}\mathbf{Mcorr}}$$

$\mathbf{M_x}$	Value of the parameter to be estimated
$\mathbf{M_{saw\_mean}}$	Arithmetic mean of the parameter of existing data for the same subject, activity and type of work site
$\mathbf{M_{x\_corr}}$	Value of the correlating variable
$\mathbf{M_{corr\_mean}}$	Arithmetic mean of the correlating parameter for the same subject, activity and type of work site
SDlog$\mathbf{M_{saw}}$	Standard deviation of the parameter for the same subject, activity and work site
SDlog$\mathbf{M_{corr}}$	Standard deviation of the correlating parameter for the corresponding subject, activity and work site

Table S1: Coefficients of linear regression models between logarithmized work shift averages of air pollutants, noise and meteorological parameters

independent var ↓	dependent var →	$logPM_{2.5Realtime}$	$logPM_{2.5\ Mass}$	logPNC	L_{eq}	logCO	$logNO_2$	$logO_3$[a]	logEC	logOC	Temperature	Humidity
	slope		0.58	0.68	1.36	0.49	-0.14	0.26	0.00	0.38	0.87	-0.32
$logPM_{2.5Realtime}$	intercept	-	1.64	8.31	79.02	-2.47	4.49	1.12	1.33	1.57	16.74	52.21
	Root MSE[b]		*0.32*	*0.73*	*4.95*	*0.69*	*0.46*	*0.79*	*0.63*	*0.38*	*5.92*	*10.14*
	Slope	1.27		0.87	1.53	0.74	-0.11	0.47	0.05	0.46	2.35	-1.61
$logPM_{2.5\ Mass}$	Intercept	-1.08	-	7.53	78.27	-3.48	4.39	0.25	1.16	1.27	11.00	57.33
	Root MSE[b]	*0.47*		*0.78*	*4.98*	*0.71*	*0.47*	*0.76*	*0.61*	*0.43*	*5.72*	*10.00*
	Slope	0.63	0.38		2.13	0.52	-0.04	-0.00	0.00	0.33	-0.25	2.15
logPNC	Intercept	-3.00	-0.22	-	61.04	-6.31	4.40	2.14	1.32	-0.53	22.92	27.61
	Root MSE[b]	*0.70*	*0.52*		*4.64*	*0.69*	*0.47*	*0.83*	*0.61*	*0.41*	*5.91*	*9.85*
	slope	0.04	0.02	0.08		0.06	-0.00	-0.00	-0.02	0.02	-0.16	-0.04
L_{eq}	Intercept	0.13	1.90	4.53	-	-5.45	4.16	2.25	2.62	1.67	33.53	54.68
	Root MSE[b]	*0.90*	*0.62*	*0.88*		*0.80*	*0.47*	*0.83*	*0.61*	*0.51*	*5.86*	*10.06*
	slope	0.62	0.41	0.66	1.83		-0.03	0.30	-0.03	0.36	1.91	-2.15
logCO	Intercept	4.24	4.15	11.32	85.03	-	3.94	2.26	1.35	3.27	21.16	49.93
	Root MSE[b]	*0.77*	*0.53*	*0.77*	*4.50*		*0.47*	*0.79*	*0.61*	*0.42*	*5.72*	*9.96*
	slope	-0.53	-0.20	-0.17	-0.30	-0.09		-0.05	0.82	0.01	-0.93	-0.25
$logNO_2$	Intercept	5.96	4.70	11.59	85.41	-0.21	-	2.30	-1.89	3.00	23.80	52.03
	Root MSE[b]	*0.89*	*0.62*	*0.95*	*5.01*	*0.85*		*0.83*	*0.51*	*0.52*	*5.90*	*10.06*
	slope	0.32	0.29	-0.01	-0.07	0.33	-0.02		-0.10	0.08	4.96	-6.43
$logO_3$	Intercept	3.21	3.30	10.92	84.38	-1.27	3.98	-	1.56	2.90	9.92	64.31
	Root MSE[b]	*0.89*	*0.59*	*0.96*	*5.07*	*0.81*	*0.47*		*0.61*	*0.51*	*4.40*	*8.65*
	slope	0.01	0.05	-0.01	-0.81	-0.06	0.40	-0.15		0.11	0.30	3.10
logEC	Intercept	3.89	3.84	10.93	85.22	-0.50	3.44	2.30	-	2.91	19.83	46.69
	Root MSE[b]	*0.93*	*0.63*	*0.97*	*5.09*	*0.86*	*0.38*	*0.81*		*0.51*	*5.97*	*9.29*
	slope	1.23	0.68	1.14	1.60	0.99	0.01	0.20	0.21		1.19	-1.72
logOC	Intercept	0.12	1.81	7.42	79.33	-3.59	3.91	1.51	0.71	-	16.55	55.82
	Root MSE[b]	*0.68*	*0.53*	*0.76*	*5.05*	*0.69*	*0.47*	*0.81*	*0.61*		*5.94*	*9.51*
	slope	0.02	0.03	-0.01	-0.12	0.04	-0.01	0.09	0.00	0.01		-0.50
Temperature	Intercept	3.46	3.36	11.05	86.59	-1.36	4.07	0.26	1.28	2.87	-	61.16
	Root MSE[b]	*0.92*	*0.61*	*0.96*	*5.02*	*0.82*	*0.47*	*0.54*	*0.62*	*0.52*		*9.61*
	slope	-0.00	-0.01	0.02	-0.01	-0.02	-0.00	-0.05	0.02	-0.01	-0.17	
Humidity	Intercept	4.02	4.22	9.92	84.80	0.20	3.97	4.76	0.49	3.31	29.00	-
	Root MSE[b]	*0.93*	*0.63*	*0.94*	*5.07*	*0.83*	*0.47*	*0.68*	*0.58*	*0.52*	*5.65*	

grey cells: spearman correlation > ±0.4 ($p<0.01$)

[a] tobit regression model with lower censoring limit to account for values below quantification limit (7.6 ppm for O_3; 3 µg/m^3 for EC)

[b] root mean squared error